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Master Thesis

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Coal gasification in entrained flow gasifiers simulation & comparison

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HÖGSKOLAN I GÄVLE

Sworn Declaration

I hereby declare to have made the present work independently and without assistance from third parties. Thoughts and quotes that I have taken from other sources directly or indirectly are identified as such. I hereby agree that the work can be made available to the public through the department of Energy Systems of the Technical University of Munich, as well as through the Universidad de Zaragoza in Zaragoza(Spain) and Högskolan i Gävle in Gävle(Sweden).

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Acknowledgments

This work has been carried out as my diploma thesis for the department of Energy Systems from the Technical University of Munich, Germany. It will also be considered as my final thesis in the Universidad de Zaragoza from Zaragoza, Spain, as well as, my final thesis in my Master in Energy Systems in the Högskolan i Gävle from Gävle, Sweden.

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Abstract

This thesis, called *Coal gasification in entrained flow gasifiers, simulation and comparison* develops a series of simulations about the gasification process and its combination with combined cycle power plants. Different process simulations have been carried out with the software ASPEN Plus.

Every simulation has been made under the same general conditions, what allows a valid comparison between the results obtained in the study. This conditions include the software parameters, such as calculation method, as well as, the same input conditions for the different input streams, the same properties for every equipment used, like pumps, gas turbine, steam turbine, heat exchangers and so on.

4,53 MW of Illinois coal is feed to the process. Every input air stream used in the process has a predefined conditions of 25°C and 1 bar, the same conditions are considered for the input water streams. The amount of air or water used in each simulation varies depending on the gasifier used in every simulation. The solvent used for the physical absorption of CO_2 and H_2S is injected at 1 bar and 10°C.

The GE gasifier based IGCC plant with slurry feed, developed by GE, consists of: Drying and crushing coal unit, slurry preparation, GE gasifier, water quenching, shift reactor, syngas clean-up unit, combustor, gas turbine, and steam cycle. The coal is dried up until 10% of moisture and then is crushed to an adequate particulate size. After that, it is mixed with water until just 65% of the mix is coal and then compressed to 55 bar. The slurry feed is injected to the GE gasifier at 55 bar and 1400°C, where it is oxidized with oxygen coming from an Air Separation Unit(ASU). The hot syngas obtained is mixed with water in order to be quenched(water quenching method) to 300°C, before the shift reactions can take place. In the shift reactor all COS and CO is converted, and the outgoing gas in that point is mainly composed of H_2, CO_2, H_2O and some sour components. This shift reactions are carried out so the clean up with a rectisol process can be accomplished. The cleaning up is performed in two stage, first stage where most of H_2S is absorbed and a second one where CO_2 is separated from the syngas. The cleaned syngas is burnt in air, and some extra nitrogen is added to the exhaust gases to cool them down until 1400°C. Moreover, this nitrogen is used to increase the mass flow of the exhaust gases and consequently increase the power output of the gas turbine. The high temperature gases after leaving the gas turbine(around 620°C) are cooled down until 100°C in three heat exchangers. The heat delivered from the exhaust gases is used in a steam cycle. The cycle has three stages with reheating between each of them.

The second simulation is a Shell gasifier based IGCC plant with dry feed, developed by Shell. The blocks used in this simulation are the same as the ones used for the GE gasifier based IGCC plant, but with dry feed preparation instead of slurry feed preparation. Moreover, a heat recovery unit replaces the water quenching in case of the Shell gasifier based IGCC. The coal is dried up until 2% before crushing and then it is mixed with an inert gas(CO_2 has been chosen) before it is compressd to 40 bar. Once the high pressure mixture is prepared it is injected to the Shell gasifier working at 40 bar and 1500°C, where it is also oxidized with oxygen coming from the ASU. The hot gases obtained are mixed with recycled quenched syngas to cool them down until 900°C. Afterwards, these syngas goes through a heat exchanger called heat recovery unit where the syngas is finally quenched to 300°C. As in the GE gasifier based IGCC, the shift reactions take place after that, but in this plant, some steam is needed to be added to the shift reactor to accomplish the conversion of the CO and COS. Downstream the shift reactor, the process is identical to the one explained for the GE gasifier based IGCC plant.

Based on the results obtained in this simulations the Shell gasifier based IGCC plant has a higher electric efficiency(38,37% versus the 34,08% obtained for the GE gasifier based IGCC plant) and also a bigger cold gas efficiency(from 79,09% to 73,64%). Considering this results Shell gasifier based IGCC plant would be better than the GE gasifier based IGCC plant, however there are more considerations have to be taken into account, such as the lower capital cost for the GE gasifier or the CO_2 capture efficiency achieved. For the Shell gasifier a CO_2 capture efficiency of 70% has been reached meantime for the GE one, this efficiency is 88,69%. This is because there is methane present in the syngas coming from the Shell gasifier that produces CO_2 in the combustor that goes to the stack without being captured. If this problem wants to be avoided an extra steam methande reforming unit should be included before the acid gas removal unit.

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Chapter 1

Introduction

1.1 Motivation

Global warming refers to the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of greenhouse gases in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change.Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer. (EPA)

Global warming is mainly caused by greenhouse gases. This gases are produced in lot of different ways every day , but as it is shown in the figure 1.1 more than 25% of the greenhouse emissions are coming from the energy supply system, which includes, combined cycle power plants. Roughly speaking the greenhouse gases emitted by human activities are divided as it is shown in the figure 1.2.

The climate change is a long-term problem that will gravely affect every one, so every effort dedicated to the reduction of greenhouse gas emissions should be welcomed. One of the main fields where it is currently been working is in the substitution of fossil fuel power plants for renewable energies sources, but this is not always possible. Some areas are not suitable for the installation of wind mills, photo voltaic plants, solar plants or hydro power generation among others. As well, nowadays, a fuel based power generation is needed in order to have a stability that renewable energies cannot grant.

Combined cycle power plants are one of the most important fuel based power plants working all around the world. This plants are in some cases over the limit of greenhouse gas emissions. However, an update to this technology is currently being highly developed by great companies like GE, Shell, Lurgi, Linde, etc... IGCC power plants have low gas emissions, mainly steam is in the flue gas when a CO_2 unit is installed in the power plant.

IGCC is a technology based in the classic combined cycle, but before the going through the boiler and being burnt, the fuel is treated in a gasifier that convert the original fuel in the so called syngas. The exhaust gases formed after the combustion of this syngas are cleaner than for a conventional combined cycle power plant.

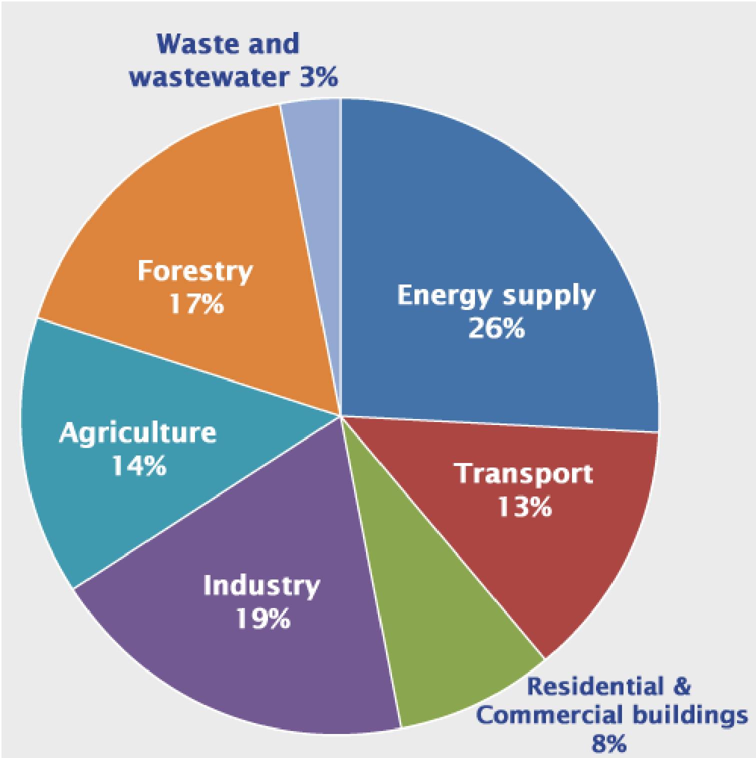

Figure 1.1: Emissions of Greenhouse gases by source, (EPA)

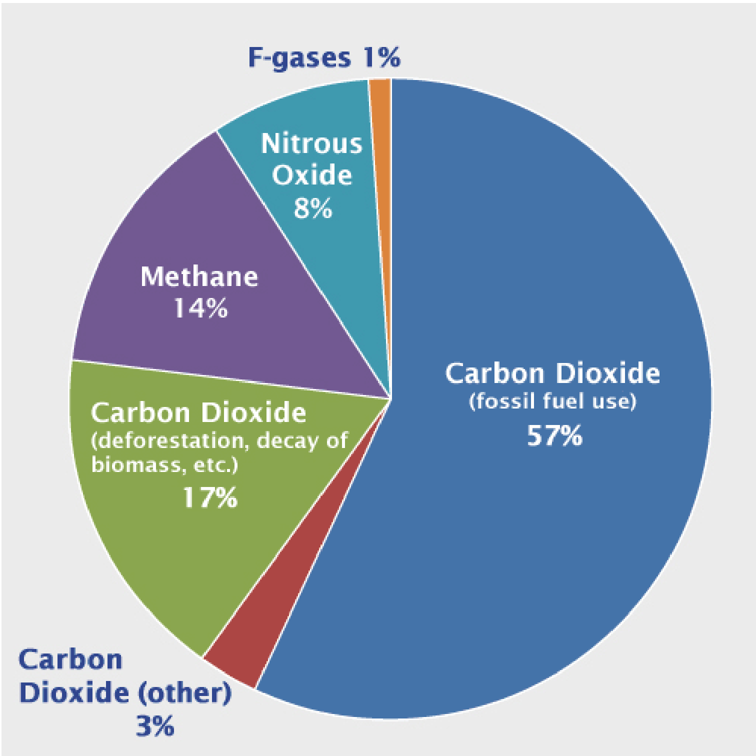

Figure 1.2: Emissions of Greenhouse gases by gas, (EPA)

So all along this document, a study of efficiencies, emissions and different feedstocks possibilities for a IGCC power plant has been presented. It has been another effort dedicated to the possibility of generating *clean electricity*.

1.2 State of the Art

In 1850 gasification process started to be used in order to produce *town gas* for lighting and heating in the cities. But one of the most important moments for the development of the gasification process was during the WWII. German engineers, due to the lack of petrol and the high availability of coal, worked in the gasification process that would allow the production of a synthetic gas that could be used as combustibles. Some years later during the *Arab Oil Embargo* and the crisis of the energy, EEUU government made great investments in the development of the first IGCC plants. Around 1990 American and European governments provided financial help to those companies that were working in the demonstration of the suitability of IGCC plants. Nowadays, private companies are working in the development of this process, because as well as decreasing the harmful emissions, this power plants can work with low rank fuels like petroleum coke and other residual hydrocarbons.

1.3 Problem definition

(Government 2010) The Climate Change and Greenhouse Gas Reduction Act 2010 establishes emissions reduction targets for the ACT of:

- zero net greenhouse gas emissions by 2060
- peaking per capita emissions by 2013
- 40% of 1990 levels by 2020
- 80% of 1990 levels by 2050.

In 2010, the Australian government published the objectives described above. As well as Australia, in most of the developed countries in the world have set the same kind of goals.

As it has been explained in the chapter 1.1, a great part of the greenhouse emissions are produced by the energy production system. One of the opportunities of reducing these emissions is the possibility of using IGCC plants instead of the conventional combined cycle plants. But for further CO_2 emissions reduction a CO_2 capture unit has to be installed in the IGCC plant, which considerably reduces the thermal efficiency of the power plant.

In this thesis different feed stocks, quenching methods and gasifier types have been used in an IGCC plant with CO_2 capture. The point is to compare and optimize them to reach the maximum efficiency possible. Once an acceptable efficiency has been obtained, in different simulations, a discussion about whether the values obtained for each model encourage the development of further investigations for that specific model is explained. the In order to accomplished these comparisons, ASPEN Plus has been the software chosen for the development of the different process configurations.

NOTE It is important to understand that the results obtained in different simulations carried out in this project are to be used to obtained a conclusion after compare them. So it should be remarked that any other comparison with other simulations or with real values has not to be done, because the conclusions obtained could be wrong. The conclusions obtained along this work will help as a starting point for further investigations, but not to take definitive decisions in real plants or prototypes. Every consideration and assumption used in the different simulations is explained along this document.

1.4 Time Frame of the Project

Before starting to work with the real study of this simulations a practical knowledge ASPEN Plus and a theoretical knowledge about the different topics that have been treated in this document had to be accomplished. Different papers about for example, gasification, feedstock preparation or CO_2 separation were read. As well, working with different ASPEN Plus tutorials and reading the main concepts in the ASPEN Plus user guides was needed to acquire the proper skill with the software.

The timetable of this project is explained in the table 1.1

Table 1.1: Intro: Mission statement

Time frame		**Objective**
Begin	**End**	
02.04.12	23.04.12	Literature review
23.04.12	14.05.12	Learning ASPEN software
14.05.12	02.07.12	Simulation of entrained flow gasifier with Slurry feed(GE)
02.07.12	12.07.12	Simulation of entrained flow gasifier with dry feed(Shell)
12.07.11	08.08.12	Elaboration of the final report
08.08.11	21.08.12	Preparation of the final presentation

Chapter 2

About ASPEN Plus

Aspen Plus is a market-leading process modeling environment for conceptual design, optimization, and performance monitoring for the chemical, polymer, specialty chemical, metals and minerals, and coal power industries (Tech.).

Aspen Plus is a useful software tool that is used to perform simulations that allow the optimization of a process. Some parameters as, cold gas efficiency, total thermal efficiency or which temperature and pressure levels should be set in the process in order to provide the best results possible can be obtained with Aspen Plus. Every energy or mass balance, thermodynamic or physical property, chemical reaction, etc... are solved by the software in the same simulation. Along this final thesis four different simulations related with coal and biomass gasification have been studied. (Orcajo 2011)

Aspen Plus is a complex simulation software, so a training period between two and four weeks should be accomplished in order to achieve a good command with the software. On the Internet several Aspen Plus tutorials can be found, which would help to get an efficient and fast training process. The knowledge about the software can be completed with the user guide provided by the developer of the computer program, (tech 2003).

2.1 User Interface

Aspen Plus has an easy-to-use interface, that allows a quick general view of the process simulation that it is being carried on, as well as a flexible manipulation of the different parameters included in it. The user interface consists mainly of two parts:

Flowsheet The blueprint of the process that it is going to be simulated is called flowsheet. Here, every operation unit, heat, work and material streams, as well as every connection between them are shown. Through the flowsheet the access to every part of the simulation and its features is eased.

After running the simulation a quick view of the results can be get thanks to the flowsheet due to each stream and operation unit is labeled with the different values of pressure, temperature, mass flow, heat, etc... with which they are working at.

Data Browser In the data browser every single parameter needed in the simulation has to be filled. The first fields that are needed to be specified are the system of units that are going to be used and the stream class. After this, every chemical component that is going to be used during the simulation needs to be included, specifying if it is conventional, non conventional or solid. Aspen Plus incorporates a incredible wide database for the convectional components, meanwhile non conventional are to be defined by the user, allowing the possibility of creating any new component.

Once the unit system is set and the chemical components are defined, the characteristics of the source streams have to be specified as well as the parameters that determined each block present in the simulation. When every field has been filled the simulation can be run.

When the simulation has been run, the results are obtained. The variation of the input data will echo in the results. So the user can compare and study the influence of every parameter in the simulation. Working with simulation software saves a lot of time and resources, a power plant can be simulated during the development, research, design or production stage instead of carrying real experiments or working in pilot plants.

Chapter 3

IGCC Power Plants

3.1 Abstract

An integrated gasification combined cycle(IGCC) process technology uses the basics of a combined cycle power plant, but instead of a direct combustion of the fuel IGCC uses a gasifier to produce a synthesis gas from the fuel, known as syngas. The syngas is mainly obtained from coal but there are some other coal-based products that can also be used for syngas production. The main purpose of this technology is to reach the same efficiency as a conventional combined cycle plant but reducing the emissions to the atmosphere with the lowest capital cost possible. The syngas mainly composed by H_2 is burned producing cleaned exhaust gases(N_2 and H_2O mostly).

In the majority of the IGCC plants, the oxidizer used in the gasifier is O_2, so an ASU is needed. There are three different types of gasifier, fixed bed gasifier, fluidized bed gasifier and entrained flow gasifier, which will defined the properties(temperature, pressure, particle matter, etc...) present in the outlet gas stream. The gas obtained from the gasifier cannot be used directly, it needs a treatment. Before reaching the gas turbine unit, it is quenched and cleaned. The quenching can be accomplished by a water injection, at which the water is mixed with the gas. Another quenching method is combined with heat recovery, which uses low temperature cleaned gas to reduce the temperature of the gas leaving the gasifier and then it goes through a radiant cooler, where steam is obtained for the steam cycle. The clean up of the gas is executed in different stages. At first stage, after the quenching, the particulate matter is removed, with candle filters and water scrubbers, secondly a shift reaction is taken place, so the sulfur products and the CO_2 can be easily removed in the final stage, with an acid gas removal unit, which uses methanol as solvent for a physical absorption.

3.2 Combined Cycle Power Plant

In the electric power generation field, it is known as combined cycle the assembly of a gas turbine and a steam cycle working at the same time. The basic sketch of combined cycle is represented in the figure 3.1. As it is shown, the fuel(coal, natural gas, biomass, etc...) is burned in the gas turbine cycle producing some net work(W-1). Afterwards, the exhaust gases from the gas turbine, that still have a high heat value are led to a heat recovery steam generator (HRSG) where, the water from the steam cycle is heated up in order to turn to steam that is driven into a steam turbine, producing extra work(W-2). The heat delivered in the condenser of the steam cycle can also be used if there is a need of low quality heat in some nearby industry.

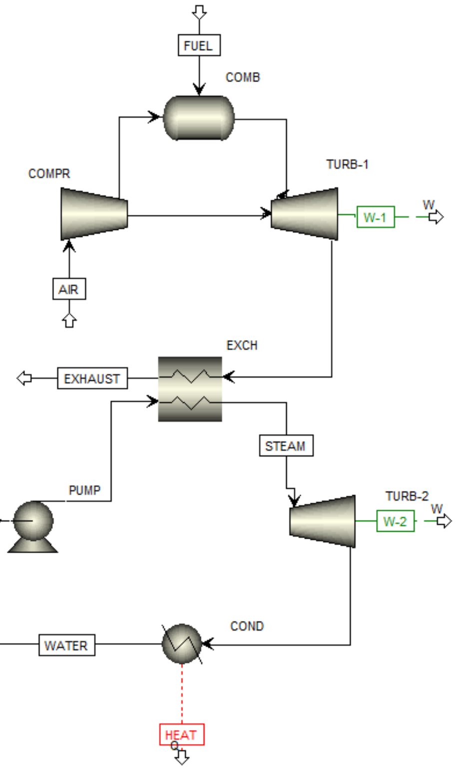

Figure 3.1: Basic sketch of a Combined Cycle Power Plant

The exhaust gases from the gas turbine are the product of a carbon based fuel combustion, therefore its chemical analysis shows that there is a high amount of CO_2 and CO on it as well as some other contaminants such as NO_x, SO, SO_2, etc... The environmental laws are getting more restrictive every time, so the necessity of reducing these emissions have become really important. Two basic choices have been arisen, the pretreatment of the fuel or the post treatment of the exhaust gases. The second option is the one that is more commonly used despite its high economic impact, meanwhile the first choice is nowadays on development. This thesis treats about the pretreatment of the fuel to produce the so called syngas through gasification process.

3.3 Gas Integration

As it is mentioned above, there is an on development process for gasification. *Gasification is a process in which combustible materials are partially oxidized or partially combusted. The product of gasification is a combustible synthesis gas, or syngas. Because gasification involves the partial, rather than complete, oxidization of the feed, gasification processes operate in an oxygen-lean environment.* (Philips). The different products between a gasification and combustion can be seen in the figure 3.2. But the gasifier is not a block that works by itself, it needs some auxiliary blocks, like the air separation unit (ASU), the CO_2 capture unit, the shift reactor, etc... as it is shown in the section 3.4. After the final syngas is obtained, which mostly consists of H_2, the product is led to the power unit, the gas turbine is combined with the steam cycle. (of Energy und electricity company) and (of Energy und Venture)

	Combustion	Gasification
Carbon	CO_2	CO
Hydrogen	H_2O	H_2
Nitrogen	NO, NO_2	HCN, NH_3 or N_2
Sulfur	SO_2 or SO_3	H_2S or COS
Water	H_2O	H_2

Figure 3.2: Comparison of the primary products created by the main fuel constituents in combustion and gasification. (Philips)

3.3.1 Types of gasifiers

There are three generic kinds of gasifiers, Fixed Bed gasifier(also known as Moving Bed gasifier), Fluidized Bed gasifier and Entrained Flow gasifier.

Fixed Bed gasifier is a counter current flow gasifier. In this type of gasifier the air is blown at the bottom, meanwhile the coal is supplied at the top. The gas leaves the at one side of the gasifier and the ash at the bottom. The pulverized coal is preheated before it gets the gasification zone due to this counter current flow configuration, however this also makes the gas leaving the gasifier having less temperature than the one needed for gasification process, around 550°C. A diagram of this gasifier configuration is shown in the figure 3.3.

Fluidized Bed gasifier is the less commercially developed gasifier because it operating flexibility is reduced. As in the fixed bed gasifier the air is blown at the bottom of the gasifier, but the amount of air needed is higher in order to maintain the coal particles injected floating within the bed. The temperature in the gasification zone is uniform around 1000°C. The ash leaves at the bottom and the gas at the top. A diagram of this gasifier configuration is shown in the figure 3.3.

Entrained Flow gasifier is the kind of gasifier studied in this thesis. GE and Shell are currently working with this technology. A fine coal size distribution at the entrance of the gasifier is needed. Both, air and fuel, are injected at the top of the gasifier, so the particle are heated up really fast. The temperature is high enough, around 1400°C, to transform the ash into slag and to achieve the highest carbon conversion. The residence time is in the order of seconds, so the high temperature is needed. The main advantage of this kind of gasifier, besides its high carbon conversion, is the flexibility for working with every rank of coal. A diagram of this gasifier configuration is shown in the figure 3.3.

3.4 IGCC blocks and components

The auxiliary blocks that a IGCC power plant needs depends on the type of gasifier that it is being used. For example, the kind of gasifier defines the outlet temperature of the gas, so the

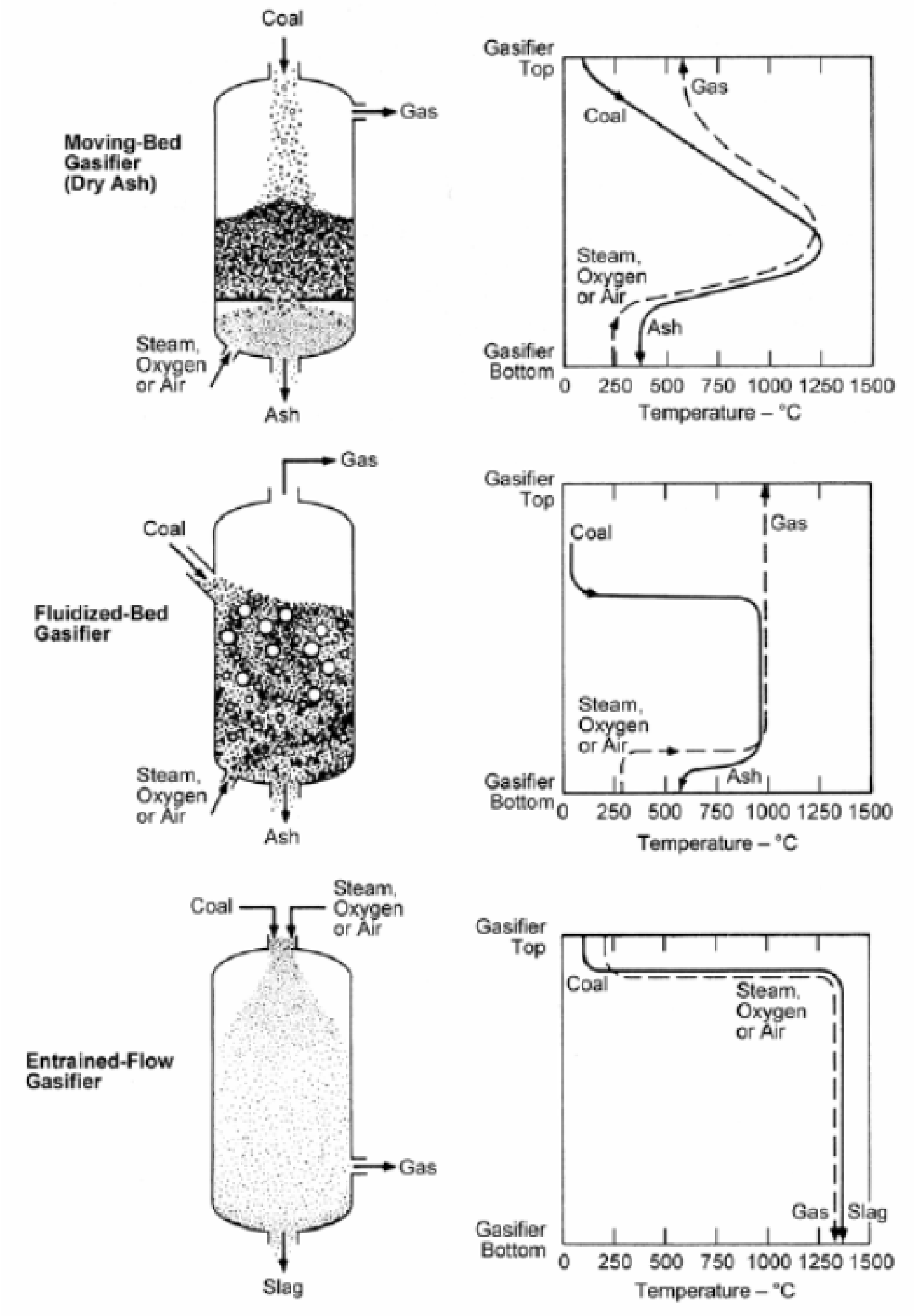

Figure 3.3: Diagrams of the different types of gasifier. (Maustard)

way of quenching this gas will depend on the temperature. As far as this thesis is related with entrained flow gasifiers, the blocks that are going to be explained below are the ones used within this gasifiers.

3.4.1 Air Separation Unit (ASU)

The oxygen needed for the gasification can be supplied by an oxygen stream or an air stream. The air blown gasifiers have less capital cost due to the the ASU is an expensive unit but the calorific value reached in the outlet gas is considerably lower, because the nitrogen dilutes is. It also have a negative effect in case of using a CO_2 capture unit. These are the reason why an ASU is used to provided an high purity oxygen stream to the gasifier.

The atmospheric air usually enters to the ASU with a rough composition of 79% N_2 and 21% O_2 and with 1 bar of pressure. The ASU is a unit that destillates the air at high pressure (around 6 bar) and cryogenic temperatures, allowing to get an outlet stream of high O_2 purity at around 6 bar. This unit consums a high amount of work in order to accomplished the separation process, during the compression of the air, however the efficiency of the plant is increased due to the higher quality of the syngas obtained. Moreover, the stream of N_2 obtained can be used in the gas turbine to get a larger power output from it.

3.4.2 Gas quenching

Independent of the gasifier used, the outlet temperature of the gas is too high(from 600°C to 1500°C) for the conventional acid gas removal systems, so the gas has to be cooled down until 100°C approximately. Also in the case of the entrained flow gasifiers, due to its high outlet temperature, the slag is in liquid form, so it is also need to reduce the temperature in order to solidify it and do not damage the downstream process equipment. There are two main quenching methods considered in this thesis, water quenching and heat recovery.

Water quenching is the method where water is mixed with the high temperature gas. Part of the sensible heat of the syngas makes the water vaporized, reducing the temperature of the stream. At this point the gas is saturated with water, at it has to go trough a series of condensers. However, if CO_2 capture is required the amount of steam present in the stream(ratio H_2O/CO) is near to the optimum, so no extra steam is needed to be add in the shift reactor.

Heat recovery is the method where the syngas after the particle removal stage at a temperature around 300°C is recycle, compressed and mixed with the 1500°C syngas stream exiting from the gasifier. So that a final gas stream of 900°C is obtained. Afterwards, this stream is cooled down by passing trough a radiant boiler where saturated steam is generated.

3.4.3 Particle removal

When a gas stream has particulate matter, it can cause problems in the downstream process and damaging the equipment, such as the gas turbine. Therefore, this particles need to be removed using dry or wet solids removal systems.

Dry solid removal systems are mainly candle filters. This systems should work between 300°C and 500°C.

Water scrubbers are the most used wet solid removal systems. They operate at lower temperatures, and in most of the IGCC plants, they are also installed after the candle filter in order to guarantee a finer removal.

3.4.4 Shift reactor

The shift reactor is the unit needed before the sulfur removal and the CO_2 capture. In this unit the chemical reaction shown in 3.1 takes place. More H_2 is produced decreasing the amount of CO in the syngas. A H_2O/CO ratio close to 2 is needed to perform an appropriate conversion. If there is a lack of H_2O then some steam from the steam cycle has to be extracted. The shift reaction ideally takes place at low temperature around 200°C.

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{3.1}$$

In order to get a proper sulfur removal the COS present in the syngas should be conversed into H_2S. This can be achieve by two different methods, with hydrolysis, which would be suitable if no CO_2 capture is considered, and a sour shift conversion, shown in the equation 3.2. This reaction can be carried out in the same shift reactor unit as the reaction 3.1, reducing the capital cost of the installation.

$$COS + H_2O \rightarrow H_2S + CO_2 \tag{3.2}$$

3.4.5 Acid gas removal unit

In the acid gas removal unit, the sulfur components and CO_2 are extracted from the syngas stream. The separation of these components from the original stream can be carried out by a physical or a chemical absorption based on MDEA(methyldiethanolamine).

Physical absorption is the choice made in this thesis, specifically Rectisol process, using methanol as solvent. How this process work is easily understandable after knowing the absorption coefficient of methanol for different gases as it is shown in the figure 3.4. It can be observed that the sulfur components have the highest absorption coefficient, and then CO_2 has higher than the rest of them. So the gas is mixed with a methanol stream at low temperature and afterwards it is flashed in order to separate the liquid substream(methanol+sulfur compounds) and the gaseous stream(syngas+CO_2). Finally the gaseous stream containing syngas and CO_2 will be mixed with a clean methanol stream in order to extract the CO_2 from the syngas after the flashing.

Once the solvent has extracted the sulfur components and the CO_2 from the main stream, the syngas is ready to be used. However, the solvent needs to be recycle, so that, a desorption process needs to be done. In this thesis, the methanol with sulfur is stripped with steam in order to obtain a high purity methanol stream and the methanol with CO_2 is flashed at different pressure levels.

The contaminants ; CO_2 is compressed to a supercritical pressure (74bar) and then can be transport away from the plant for a the final capture, meanwhile, the H_2S is led to a Claus process plant where can be used some chemical processes.

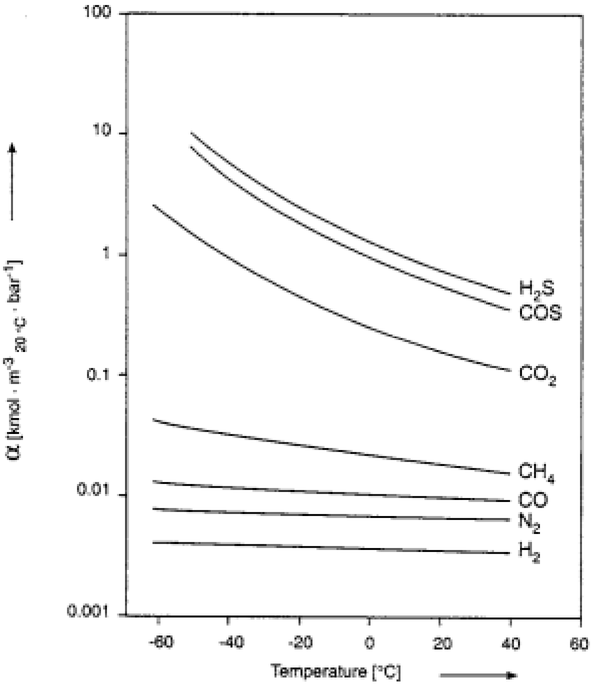

Figure 3.4: Absorption coefficient α of various gases in methanol. (N.Korens u. a.)

Chapter 4

General Assumptions

4.1 Abstract

After the different process simulations have been run, the results are to be compared. In order to have a valid comparison and get useful conclusions, some general assumptions have to be made. The energy inputs, the different blocks efficiencies, the calculation method, etc... have to be the same within each simulation.

4.2 ASPEN Plus

The flowsheet in ASPEN Plus has to be designed in every simulation and all the parameters that defined it are to be set. The first step that it is needed to be decided is the unit system that will be used along the simulation. The unit system used is Solids with Metric Units that can be found in the table 4.1. The stream class is needed to be specified when working with solids in ASPEN Plus, in this simulation the one used is MCINCPSD, which includes MIXED, CIPSD and NCPSD substreams. MIXED substreams include every material stream composed by liquid, gas or both. CIPSD and NCPSD are used to defined conventional and non-conventional solid substreams. PSD means that a particle size distribution is defined for the input solid substreams. Non-conventional solids are those who are not included in the database of the software and are needed to be specified. As well, the PR-BM property calculation method is defined, that it is based in the Peng-Robinson equation of stated with Boston-Mathias modifications.

Table 4.1: Unit system

Variable	*Units*
Temperature	°C
Pressure	bar
Mass flow	kg/hr
Mole flow	kmol/hr
Heat flow	W
Work flow	kW

Every component that is used in the simulations is shown in the figure 4.1

Define components

Component ID	Type	Component name	Formula
H2O	Conventional	WATER	H2O
O2	Conventional	OXYGEN	O2
N2	Conventional	NITROGEN	N2
COAL	Nonconvention:		
H2	Conventional	HYDROGEN	H2
C	Solid	CARBON-GRAPHI	C
S	Conventional	SULFUR	S
CO2	Conventional	CARBON-DIOXIDE	CO2
CO	Conventional	CARBON-MONOXI	CO
CL2	Conventional	CHLORINE	CL2
HCL	Conventional	HYDROGEN-CHLC	HCL
ASH	Nonconvention:		
H3N	Conventional	AMMONIA	H3N
COS	Conventional	CARBONYL-SULFI	COS
H2S	Conventional	HYDROGEN-SULF	H2S
CH4	Conventional	METHANE	CH4
NO	Conventional	NITRIC-OXIDE	NO
NO2	Conventional	NITROGEN-DIOXI	NO2
N2O	Conventional	NITROUS-OXIDE	N2O
N2O4	Conventional	NITROGEN-TETR	N2O4
N2O3	Conventional	NITROGEN-TRIOX	N2O3
CH4O	Conventional	METHANOL	CH4O

Figure 4.1: Components

4.2.1 Coal definition

Illinois Coal, defined in the book (Fan 2010), is used for these simulations. Coal is defined as a NCPSD substream due to its state is not included in the software database. Physical properties of the coal are set before any calculation can be done. Enthalpy and density are defined respectively through the HCOALGEN and the DCOALIGT models. HCOALGEN model selected, for calculate the enthalpy of the coal, needs a component attribute definition for the coal, based on a proximate analysis(PROXANAL), ultimate analysis(ULTANAL) and sulfur analysis(SULFANAL). As have been said previously, NCPSD substreams are solids with a particle size distribution that has to be specified. In this simulations a common PSD, shown in the table 4.2 obtained from the tutorial (ASPEN technology) is used.

Table 4.2: Coal PSD

Interval	*Lower Limit*	*Upper Limit*	*Weight Fraction*
7	120	140	0.1
8	140	160	0.2
9	160	180	0.3
10	180	200	0.4

Once the PSD is set, the component attribute analysis for the coal are defined in the table 4.3.

Table 4.3: Coal Component Attributes

PROXANAL		**ULTANAL**		**SULFANAL**	
Element	*Value*	*Element*	*Value*	*Element*	*Value*
Moisture	11.12	Ash	10.91	Pyritic	2.82
FC	49.72	Carbon	71.72	Sulfate	0.0
VM	39.37	Hydrogen	5.06	Organic	0.0
ASH	10.91	Nitrogen	1.41		
		Chlorine	0.33		
		Sulfur	2.82		
		Oxygen	7.75		

The attribute analysis have to fulfill the next requirements:

- PROXANAL[1] values of FC, VM and ASH must sum 100
- ULTANAL value for ASH must be the same as PROXANAL ash value
- ULTANAL values sum 100

[1]In proximate analysis, every value is given in dry basis but MOISTURE

- SULFANAL[2] values sum the ULTANAL value for SULFUR

The software can calculate the heat of combustion, as well as the rest of operating parameters needed, once the component attributes are known, but as far the heat of combustion for this specific coal is given in the book (Fan 2010), it will be set manually. This modification can be carried on changing the default values of the option Option code value from [1,1,1,1] to [6,1,1,1]. The heat of combustion has to be specified in dry basis as shown in formula 4.1

$$HCOMB(drybasis) = 29,972MJ/kg \tag{4.1}$$

The input of coal has to be equal in each simulation. In these simulation 612 kg/hr of wet coal are fed to the process, which implies 544 kg/hr of dry coal making 4,53 MW of heat input energy.

4.2.2 Air Definition

Every air stream incoming in the processes used along the simulations will be defined as a MIXED substream with the composition shown in the table 4.4.

Table 4.4: Air Composition

Element	*Weight percentage*
Oxygen	21
Nitrogen	79

4.2.3 Coal Preparation Unit

This unit includes the drying and crushing of the coal as can be seen in the figure 4.2. These unit is based in the drying unit shown in the tutorial (ASPEN technology). The WET-COAL fed into the system is dried in a RSTOIC rector until 10% of moisture content before it get crushed. A higher moisture value would difficult the crushing. This unit is defined to work with 1 bar pressure and zero heat duty. The equation 4.2 is the reaction carried out in the RSTOIC block. The total amount of coal converted will be set by a calculator block, equation 4.3, allowing that the desirable moisture content can be reached in the dry coal stream.

$$COAL(wet) \rightarrow 0.0555084 * H_2O \tag{4.2}$$

$$CONV = \frac{H_2O_{IN} - H_2O_{OUT}}{100 - H_2O_{OUT}} \tag{4.3}$$

[2] Sulfur analysis is not specified so a 100% of pyrilitc sulfur is assumed

The heat needed by the process is supplied by the hot air stream(150°C) incoming the RSTOIC reactor. In some cases these hot stream is composed only for N_2, but in these simulation, the N_2 stream obtained in the ASU will be used in the gas turbine in order to increase the power output get. Afterwards, a separator will split the the incoming stream into a solid one(DRY-COAL) and a gaseous one(EXHAUST). After the drying, the coal must be crushed in the crusher before the gasification process can start. A Hardgrove Grindability Index of (HGI) of 50, and a maximum particle diameter of 100 mu is set in the crusher, which is recommended for a entrained flow gasifier. HGI shows how difficult a particle is to grind, so the work consumption of the crusher can be calculated.

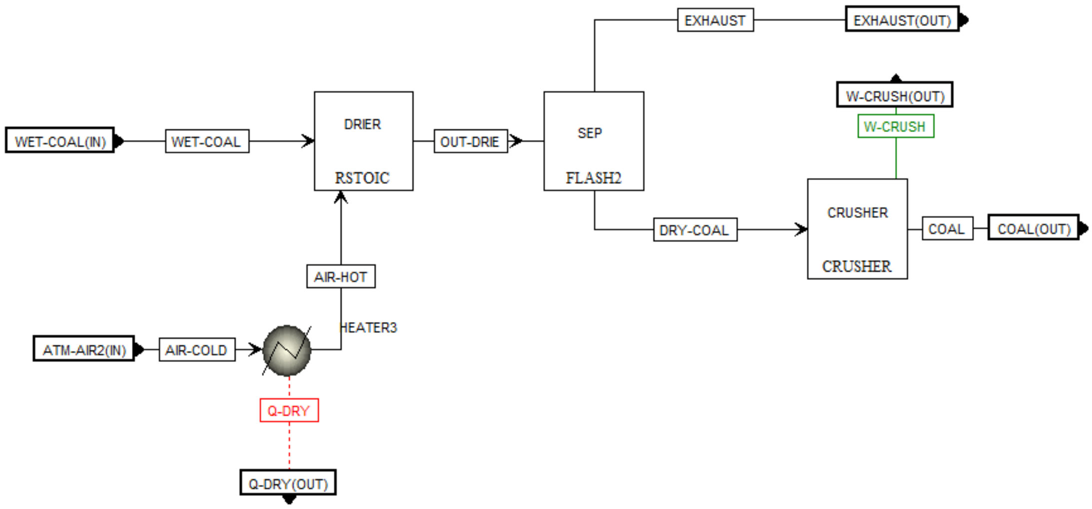

Figure 4.2: Coal Preparation Unit flowsheet

4.2.4 Air Separation Unit(ASU)

In the gasification process, use oxygen as oxidizer implies a higher efficiency, so a ASU is designed and included in the simulations. The purity of the OXYGEN stream is above 99% in order to have a higher CO_2 purity in the combustor. This seratation is done thanks to a cryogenic separation, so it is need to reach a temperature point where the oxygen is found in liquid state and the nitrogen in gaseous form. At atmospheric conditions a temperature of around -190°C should the achieve, but working at 6 bar pressure, -170°C is enough. In this flowsheet the compressor, with an efficiency of 90% compressed the air to 6 bar, and then it is cooled down until -170°C through the used of coolers and heat exchangers, the way it is shown in the figure 4.3.

Both outgoing streams have a pressure of 6 bars and a temperature around 25°C.

4.2.5 Gas Clean Up Unit

IGCC power plants are being developed with and without CO_2 capture. In these simulations, in order to reduce the emissions, the CO_2 capture has been considered. The CO_2 capture unit is also integrated with a sulfur removal unit forming the gas clean up unit.

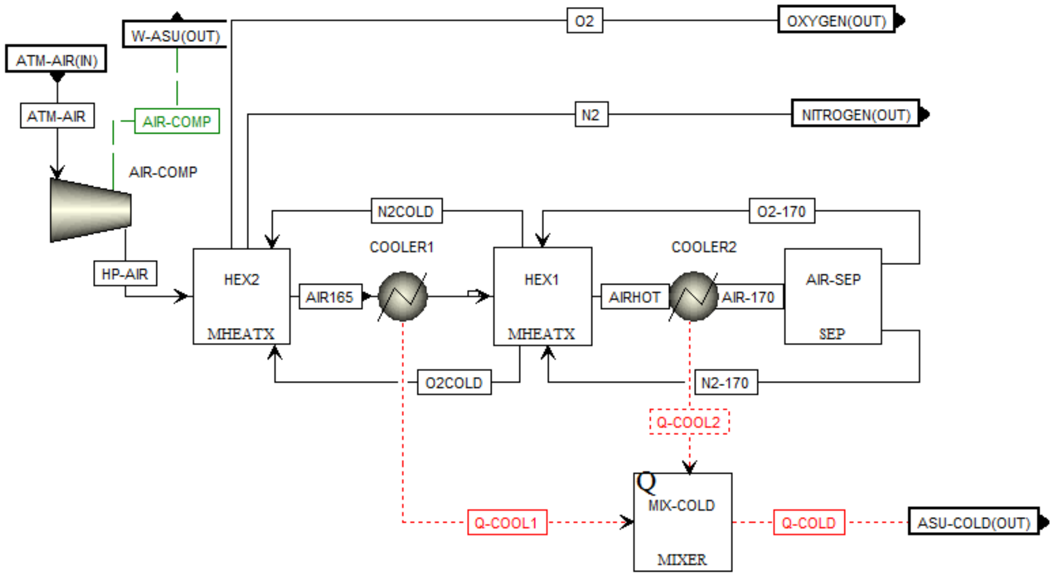

Figure 4.3: ASU flowsheet

The first step in this unit is the shift reactor, that has been represented by a RSTOIC reactor working at 250°C and 55 bar. The reactions that have been defined are indicated in the equations 4.4 and 4.5. These reactions are exothermic so heat is delivered from this block that is added to the steam cycle.

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{4.4}$$

$$COS + H_2O \rightarrow H_2S + CO_2 \tag{4.5}$$

The sulfur and CO_2 removal has been carried out with a rectisol process in different steps, absorption and desorption of H_2S and absorption and desorption of CO_2, as can be seen in the figure 4.4.

The H_2S absorption is simulated with a RADFRAC reactor working at 30 bar. Previously to the absorption the syngas is heated, until 700°C, up in order to reach a better performance for this operation. The RADFRAC is configured with 10 stages and no reboiler nor condenser. The out coming gas flow is led to the CO_2 absorber meanwhile the solvent flow is led to the desorption stage.

The H_2S desorption is also simulated with a RADFRAC rector. This block is used for cleaning the solvent so it can be recycle, reducing the amount required. The desorption is performed at 5 bar and around 100°C. The solvent stream out coming is composed mainly by water(19.9%) and methanot(80%), so it can be reused, meanwhile the gaseous stream´, holding above 99.9% of the H_2 aborbed, is led to a Claus process that will be carried out away from the IGCC plant.

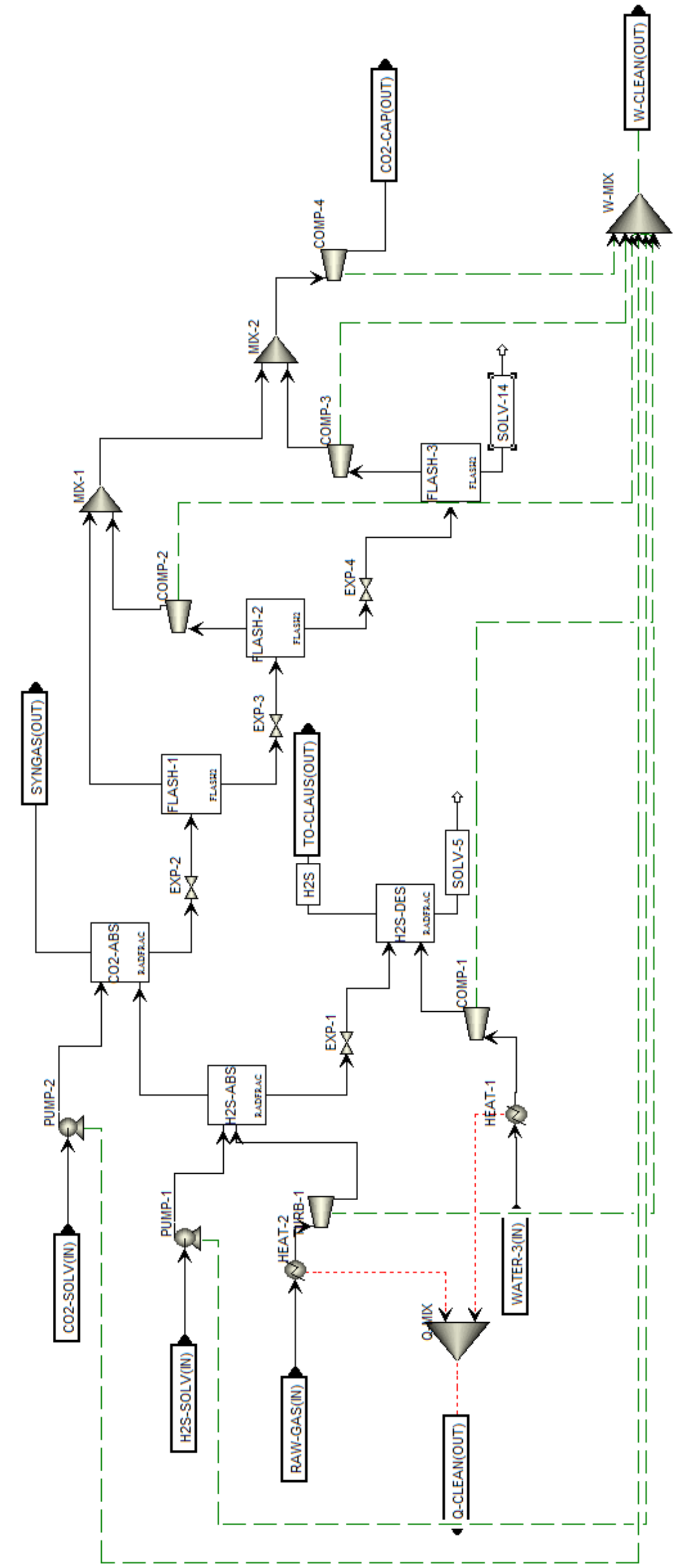

Figure 4.4: Clean Up Unit flowsheet

The CO_2 absorption is as well carried out with a RADFRAC reactor working at 30 bar. As in the H_2S absorption unit, this one is configured with 10 stages and no reboiler nor condenser. This absorption is accomplished at low temperature, around 10°C. The outgoing gaseous stream is the final syngas product ready to be burnt in the gas turbine. On the other hand, the liquid stream is led to the desorption process.

The CO_2 desorption is carried out in a three step flash chamber, that it is simulated with three FLASH2 blocks, at 15, 5 and 1 bar. The final purity of the solvent obtained after these three stages is 99%. Every CO_2 stream leaving the flash chamber is compressed until a supercritic pressure (74 bar) needed for the final transport and capture.

4.2.6 Gas Turbine

The final syngas product is mixed with the N_2 stream leaving the ASU, in order to obtain a higher power output in the gas turbine. The gas is combusted in boiler, that is represented by a RGIBBS reactor at 30 bar and 1400°C. The exhaust gases run the gas turbine, with an isentropic efficiency of 86%, from 30 bar to 1 bar developing work.

4.2.7 Steam Cycle

The steam cycle works with three steam turbines, high pressure turbine(from 140 to 30 bar), medium pressure turbine(from 30 to 5 bar) and low pressure turbine(from 5 to 0.2 bar). The stream is produced with the residual heat of the gasification process and thanks to heat exchangers utilizing the remain heat in the exhaust gases from the gas turbine. The condenser of the steam cycle is a refrigeration tower with natural flow that has no energy requirements, so it is not included in this simulation. The efficiencies of the components of the steam cycle are specified in the table 4.5.

Table 4.5: Steam Cycle components

Component	*Efficiency*
Pump	0.85
Turbines	0.90
Heat exchangers	1.0

4.3 Efficiency calculations

4.3.1 Thermal efficiency

The thermal efficiency of the system is calculated as the net output power over the input power. The net output power considers the power generated by the steam cycle and the gas turbine and also all the auxiliary consumptions such as compressors, pumps and the crusher. Every heat stream is considered as a heat gain or loss for the water stream in the steam cycle. The heat streams considered are originated in the coal preparation unit, the ASU, the slag separation unit, the shift reactor, the clean up unit and the heat recovery steam generator(just in the dry feed gasifier).

4.3.2 Cold Gas efficiency

The cold gas efficiency is the output chemical energy of the syngas over the input chemical energy of the fuel. In this simulations has been calculated using the flowsheet shown in the figure 4.5.

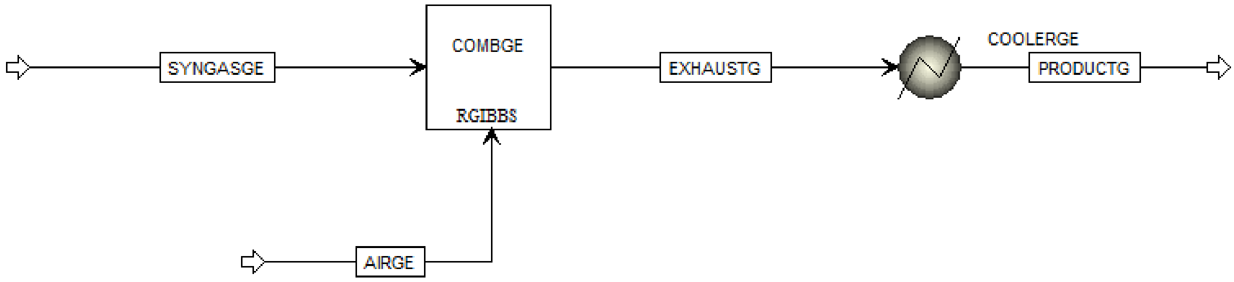

Figure 4.5: Cold Gas efficiency calculation flowsheet

The chemical energy of the input fuel is the heat of combustion of the coal multiplied by the mass flow of dry coal incoming the system. The output chemical energy remaining in the syngas is calculated simulating the combustion of the fuel at 300°C of temperature and then cooling down the exhaust gases to 300°C again. The syngas composition is considered before the shift reaction and the clean up is carried out. No pressure drop is taken into account in this process.

4.3.3 CO_2 Capture efficiency

The CO_2 capture efficiency is calculated following the formula 4.6.

$$Efficiency = \frac{CO_2 captured}{CO_2 produced} \tag{4.6}$$

Chapter 5

Entrained Flow Gasifier with Slurry Feed

5.1 Introduction

The entrained flow gasifiers are the kind of slagging gasifiers, which means that the ash is converted to slag(liquid state), so these type of gasifiers work at high temperature (1400-1600°C). Shell and GE are the main developers of entrained flow gasifiers, the first one works with dry feed gasifiers meanwhile the second is currently developing slurry feed gasifiers.

In a slurry feed gasifier after the crushing of the coal, when a appropriate particle size distribution has been gotten, it is mixed with water in order to obtain the slurry. The mixed usually has a 65% of coal and 35% of water(weigth basis). Afterwards is compressed before it is led to the gasifier.

Slurry feed gasifiers have lower efficiency than dry feed gasifiers and are needed to be used with high rank coal, otherwise the efficiency will be really low and the electricity production would not be effective. The cold gas efficiency is also lower because part of the produced syngas has to be burned in order to vaporized the water included in the mix. Meanwhile slurry feed gasifiers have a lower capital cost.

When quenching the syngas, GE gasifiers can work with a heat recovery system or with water quenching. In this simulation, water quenching has been selected, that recovers less sensible heat than the heat recovery system, however the extra H_2O present in the syngas stream is useful for carrying out the shift reaction and allow the CO_2 capture and the H_2S removal. As well, the Shell gasifier can only work with heat recovery, so in this document both systems are explained and compared.

5.2 Slurry Preparation and Gasification

The gasifier and the slurry preparation is simulated in ASPEN Plus following the flowsheet shown in the figure 5.1.

The RYIELD reactor is a unit that does not exit in the real process, but it is used for the software to convert the non-conventional solid that defines the coal into the different elements,so that the chemical reactions and the energy balances can be done properly. In this *fictional* step a problem appears in the simulation, some elements at atmospheric pressure and ambient

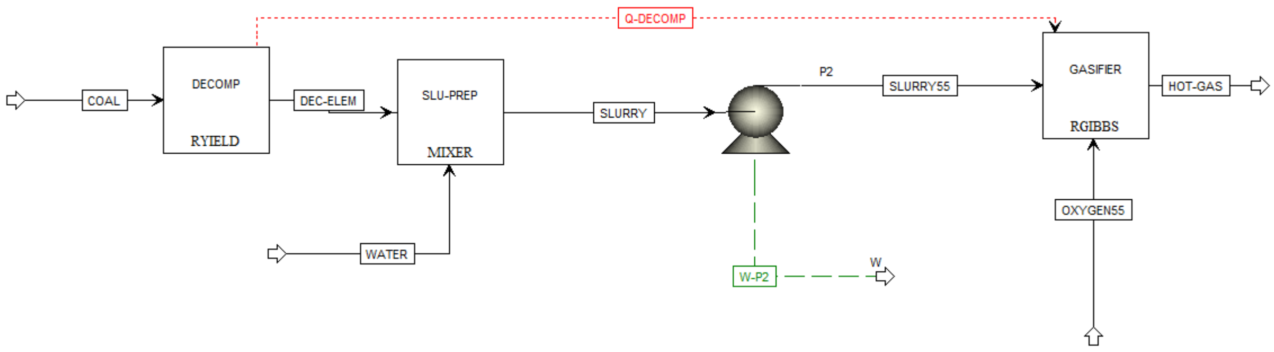

Figure 5.1: Slurry preparation and Gasifier flowsheet

temperature are in gaseous state, so after the mixing with the water for producing the slurry, some gaseous phase is present. This implies a warning advice in the compression, so in this particular pump, the option that allows the pump work with gaseous and liquid states has been activated. By the time, there is a fictional compression of gas, the temperature of the product increases much more than in a liquid compression, as well a great amount of work has to be developed by the pump. This extra work and the heating obtained from cooling down the product at 55 bar to its original temperature are neglected. This assumptions will not affect the final results, due to the work that the pump would require is too small compared with the work required for the compressors and the work developed by the turbine.

The design specifications and calculator blocks are two tools available in ASPEN Plus that allow the user to set an initial value for a specific variable and then an iteration will produce the final value for the named variable once the result required is reached. The amount of water needed for the slurry preparation is calculated with a design specification that gives the final amount of water needed to get 65% of weight of coal in the slurry. As well the amount of oxygen needed for the combustion is set with a design specification which condition is that the output gas from the gasifier has a temperature of 1400°C.

The gasification is simulated with a RGIBBS reactor working at 55 bar. The block use the phase and chemical equilibrium calculation method and allows that every component defined for the simulation can be produced with the only restriction that the carbon remaining will be in form of conventional solid.

5.3 Quenching

The quenching in this simulation, as it is said previously, is carried out with water quenching, that it is simulated with a MIXER block. In this unit, a stream of compressed steam in mixed with the produced gas. As before, the design specification tool allows to set the proper amount of steam needed to reach a final temperature of 300°C after the quenching.

Once the quenching is accomplished the simulation follows the steps specified in the chapter 4.

5.4 Results

As it is said in the section 4.2.1 the amount of input wet coal is 612 kg/hr which implies 544 kg/hr of dry coal making 4,53 MW of heat input energy. Below the results obtained in the simulations are shown.

5.4.1 Water consumption

Table 5.1: Water consumption for the IGCC plant with GE gasifier

Stream	*kg/hr/MW*
Steam cycle	70,6
Steam extra	279,4
Water quenching	184,7
Slurry preparation	42,1
Clean-up	22,6

- **Steam cycle** defines the amount of water that is used in the steam cycle and it is recirculated.
- **Steam extra** defines the amount of extra water that it is introduced in the cycle in the second and the third heat exchanger of the steam cycle in order to obtain a major power output.
- **Water quenching** is the amount of water needed to cool down the gas from the gasifier to 300°C with the water quenching method.
- **Slurry preparation** is the amount of water needed to have a proper slurry feed for the gasifier.
- **Clean-up** defines the amount of water used in the cleaning-up unit, used for the H_2 desorption.

The variable *steam cycle* is much lower than *steam extra* because, the main stream suffers a much higher temperature increment, so the mass flow has to be lower.

5.4.2 Air consumptions

- **Coal drying** defines the amount of air that is used to dry the coal before going to the crusher.

Table 5.2: Air consumption for the IGCC plant with GE gasifier

Stream	*kmol/hr/MW*
Coal drying	16,5
ASU	16,1
Combustion	23,1
Nitrogen	27,9

- **ASU** is the air used in the air used in the air separation unit to produce the oxygen needed to produced the oxidization in the gasifier.
- **Combustion** is the amount of air needed to reach a complete combustion of the syngas.
- **Nitrogen** defines the amount of NITROGEN added to the exhaust gases after the combustion to have a final temperature of 1400°C.

The extra nitrogen added to the exhaust gases after the combustion makes the mass flow going through the gas turbine to increase generating a greater power output. There is a choice of generating steam while cooling down this gases to 1400°C before the gas turbine, but in this way the power output get is lower.

5.4.3 Solvent consumption

Table 5.3: Solvent consumption for the IGCC plant with GE gasifier

Stream	*kg/hr/MW*
H_2S absorber	883,0
CO_2 absorber	1670,2
Extra solvent	143,5

- **H_2S absorber** is the amount of solvent(methanol) needed in the unit where the H_2S is separated from the syngas.
- **CO_2 absorber** defines the amount of solvent needed for the absorption of CO_2.
- **Extra solvent** defines the extra solvent that is needed to be replaced in the cycle.

After the absorption, the solvent is *cleaned*. Once the methanol leaves the H_2S absorber, it is leaded to a desorption unit to reach a high purity solvent that can be used again. Meanwhile, the solvent used in the CO_2 absorber goes 3 flash stages to be cleaned. Nevertheless, some of this solvent cannot be complete regenerated to be used again, so an extra solvent is needed for replace it.

5.4.4 Plant efficiency

The cold gas efficiency reached is 73,64%.

The CO_2 capture efficiency is 88,69%.

The total efficiency of the IGCC plant is 34,08%.

5.4.5 Summary

In the figure 5.2 a summary of all the results of the GE gasifier is shown.

	Input power	Output power		CO_2 captured	CO_2 capture efficiency	Cold Gas efficiency	Total efficiency
		Gas turbine	Steam cycle				
GE gasifier	**4,53 MW**	**2,47MW**	**0,4 MW**	**1090 kg/hr**	**88,69%**	**73,64%**	**34,08%**

Figure 5.2: Results summary for GE gasifier

Chapter 6

Entrained Flow Gasifier with Dry Feed

6.1 Introduction

As it has been said in the chapter 5, entrained flow gasifier are those which work at slagging temperature(1400-1600°C). Shell is one of the main entrained flow gasifier developers. Its gasifier works with dry feed, (global solutions 2008).

In a dry feed gasifier, the wet coal is normally dried until around 2% before the crushing. After the crushing, when a appropiate particle size distribution has been reached, the coal is mixed with an inert gas in order to be able to compress the feed to a high pressure. Aftewards, it is led to the gasifier.

In comparison with the slurry feed gasifiers, dry feed gasifiers can work with every rank of coal performing high efficiency values. The cold gas efficiency of this gasifiers is higher because no fuel is burnt to vaporize water as it happens in the slurry feed gasifiers. On the other hand, dry feed gasifiers have higher capital cost than the slurry feed ones.

Dry feed gasifiers, specifically Shell gasifiers, when quenching syngas just a heat recovery system can be used. First of all, some of the quenched syngas is recycle to cool down a bit the high temperature syngas before going through the heat recovery system.

6.2 Dry Feed preparation and Gasification

The gasifier and the dry feed preparation are simulated in ASPEN Plus following the flowsheet shown in the figure 6.1.

As it was explained in the section 5.2, the block RYIELD does not exit in the real process and it is used for the software ASPEN Plus to convert the non-conventional feed(coal) into the different elements that composed it. As it happened in the previous chapter as well, a problem occurs with this *fictional* step. The element S and a bit of H_2O diluted on it are in liquid form instead of gaseous, so they cannot be compressed in the compressor with the rest of the elements. And auxiliary and *fictional* pump is used to solve this problem, the work developed by this pump is neglected in the calculations due to it is not real.

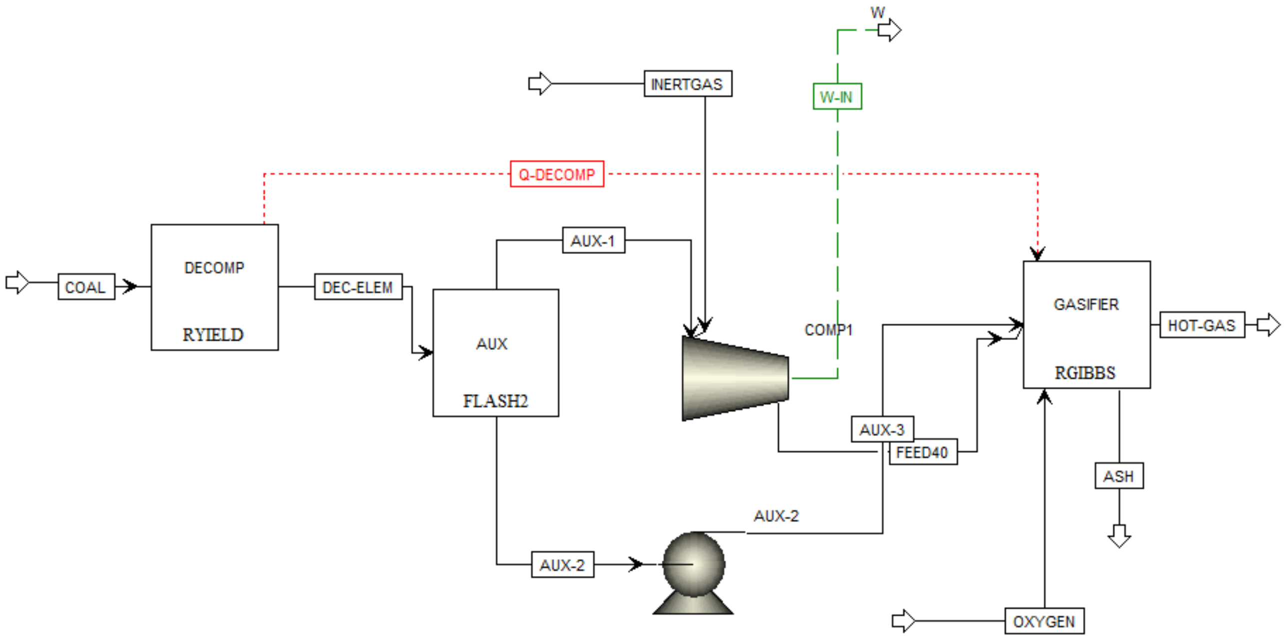

Figure 6.1: Dry feed preparation and Gasifier flowsheet

The gaseous stream is mixed with an inert gas. Nitrogen is often used for this purpose, but in the case of IGCC plants with CO_2 capture, medium pressure CO_2 extracted from the capture unit can be used as inert gas. The amount of inert gas used is fixed following the parameters explained in the article (der Drift u. a. 2004). 3,7m^3 or CO_2 are to be used per ton of coal, so 2,26m^3/hr are used.

As it was said in the section 5.2, a calculator block is used in the RYIELD block for the decomposition and a design specification is used to calculate the amount of air needed in the drier.

Once the dry feed has been compressed the gasification process is carried out in a RGIBBS block at 40 bar. The block use the phase and chemical equilibrium calculation method and allows that every component defined for the simulation can be produced with the only restriction that the carbon remaining will be in form of conventional solid. The amount of oxygen needed in the gasifier is calculated with a design specification, expecting 1500°C for the outcome gas.

6.3 Quenching

The quenching system used in this simulation is shown in the figure 6.2. It consist of the syngas quenching and a heat recovery.

The syngas quenching uses recirculated quenched syngas to cool down the hot gas to 900°C approximately. A design specification is used to calculate the fraction of quenched syngas that

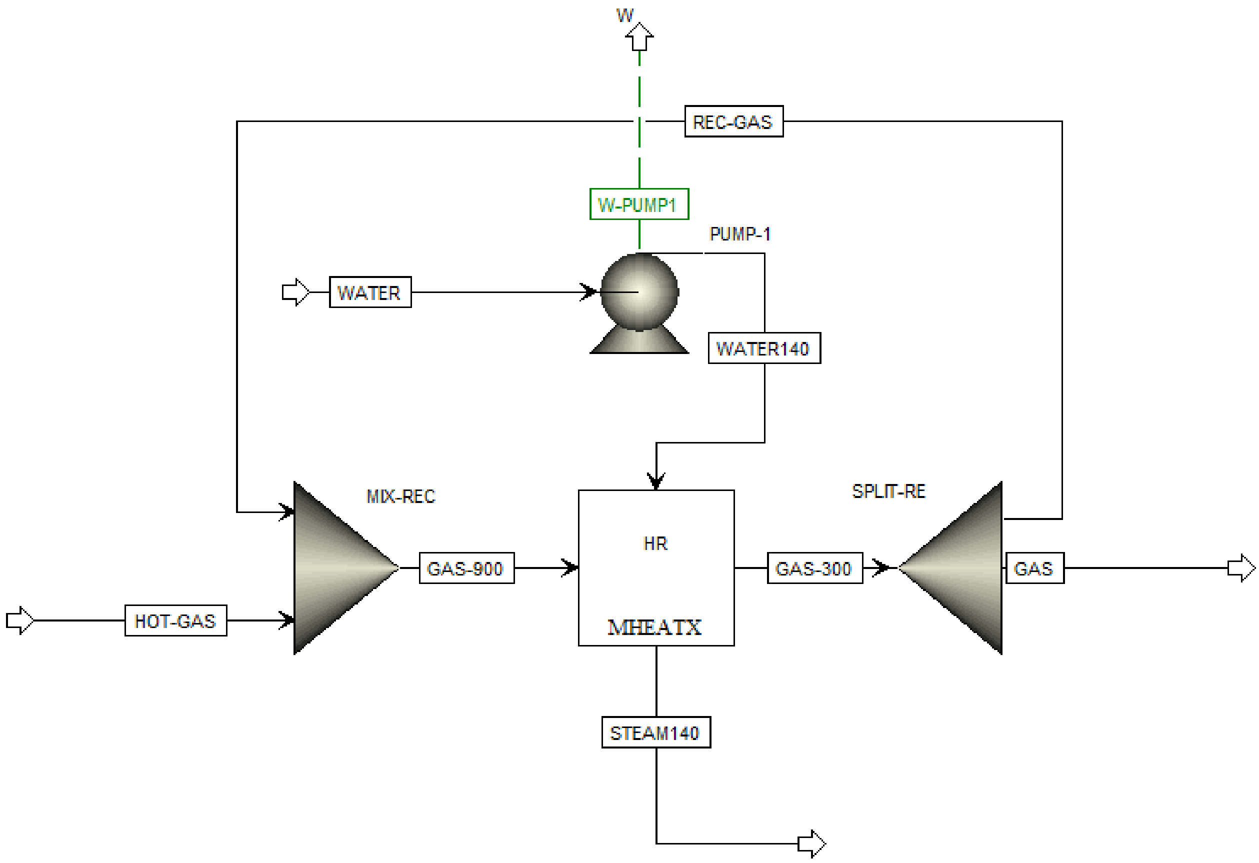

Figure 6.2: Syngas Quenching and Heat Recovery flowsheet

it is needed to be recirculated. Once 900°C are reached for the syngas, it goes through a heat recovery system that consist of a heat exchanger where high pressure steam is produced. The amount of water used in this refrigeration of the syngas is fixed by a design specification with the objective of having 575°C in the steam leaving the heat exchanger.

Once the quenching is accomplished the simulation follows the steps specified in the chapter 4.

6.4 Results

As it is said in the section 4.2.1 and as it happens in every simulation, the amount of input wet coal is 612 kg/hr which implies 544 kg/hr of dry coal making 4,53 MW of heat input energy. In the next lines the results obtained in the simulations are shown.

6.4.1 Water consumption

Table 6.1: Water consumption for the IGCC plant with Shell gasifier

Stream	*kg/hr/MW*
Steam cycle	72,4
Steam extra	273,4
Heat recovery	128,8
Shift reactor	106,0
Clean-up	22,1

- **Steam cycle** defines the amount of water that is used in the steam cycle and it is recirculated.
- **Steam extra** defines the amount of extra water that it is introduced in the cycle in the second and the third heat exchanger of the steam cycle in order to obtain a major power output.
- **Heat recovery** is the amount of water used in the heat exchanger to cool down the syngas from 900°C to 300°C.
- **Shift reactor** is the amount of water that it is needed to add to the shift reactor.
- **Clean-up** defines the amount of water used in the cleaning-up unit, used for the H_2 desorption.

The variable *steam cycle* is much lower than *steam extra* because, the main stream suffers a much higher temperature increment, so the mass flow has to be lower.

In the dry feed entrained gasifiers with heat recovery, no water or steam flow is added directly to the syngas in any step upstream from the shift reactor. As it is shown in the equations 4.4 and 4.5 for a shift reactor, H_2O is needed in this block. So steam at 40 bar is needed to be add to the shift reactor in this point. The amount used is calculated by a design specification under the condition of less than 1% of water present in the outgoing syngas stream and all the COS and CO is converted.

6.4.2 Air consumptions

Table 6.2: Air consumption for the IGCC plant with Shell gasifier

Stream	*kmol/hr/MW*
Coal drying	34,8
ASU	10,9
Combustion	26,5
Nitrogen	34,4

- **Coal drying** defines the amount of air that is used to dry the coal before going to the crusher.
- **ASU** is the air used in the air used in the air separation unit to produce the oxygen needed to produced the oxidization in the gasifier.
- **Combustion** is the amount of air needed to reach a complete combustion of the syngas.
- **Nitrogen** defines the amount of NITROGEN added to the exhaust gases after the combustion to have a final temperature of 1400°C.

The extra nitrogen added to the exhaust gases after the combustion makes the mass flow going through the gas turbine to increase generating a greater power output. There is a choice of generating steam while cooling down this gases to 1400°C before the gas turbine, but in this way the power output get is lower.

6.4.3 Solvent consumption

Table 6.3: Solvent consumption for the IGCC plant with Shell gasifier

Stream	*kg/hr/MW*
H_2S absorber	331,1
CO_2 absorber	1221,4
Extra solvent	81,4

- **H_2S absorber** is the amount of solvent(methanol) needed in the unit where the H_2S is separated from the syngas.
- **CO_2 absorber** defines the amount of solvent needed for the absorption of CO_2.
- **Extra solvent** defines the extra solvent that is needed to be replaced in the cycle.

After the absorption, the solvent is *cleaned*. Once the methanol leaves the H_2S absorber, it is leaded to a desorption unit to reach a high purity solvent that can be used again. Meanwhile, the solvent used in the CO_2 absorber goes 3 flash stages to be cleaned. Nevertheless, some of this solvent cannot be complete regenerated to be used again, so an extra solvent is needed for replace it.

6.4.4 Plant efficiency

The cold gas efficiency reached is 79,09%.

The CO_2 capture efficiency is 70,0%. This efficiency is quite low because there is some CH_4 in the syngas that is burned during the combustion and produces CO_2.

The total efficiency of the IGCC plant is 38,37%.

6.4.5 Summary

In the figure 6.3 a summary of all the results of the Shell gasifier simulation is shown.

	Input power	Output power		CO_2 captured	CO_2 capture efficiency	Cold Gas efficiency	Total efficiency
		Gas turbine	Steam cycle				
GE gasifier	**4,53 MW**	**2,47MW**	**0,4 MW**	**1090 kg/hr**	**88,69%**	**73,64%**	**34,08%**

Figure 6.3: Results summary for Shell gasifier

Chapter 7

Comparison of gasification processes

7.1 Abstract

In this thesis two different simulations have been carried out in ASPEN Plus. Two different entrained flow gasifiers integrated in a IGCC power plant have been modeled and studied. In both cases, CO_2 capture has been included . In every simulation the same general assumptions have been considered in order to be able to perform a proper analysis and comparison between them.

In this chapter all the results obtained for every simulation are compared and commented. The main points studied are:

- Water consumption
- Air consumption
- CO_2 capture efficiency
- Cold gas efficiency
- Total efficiency

Some other comments are included as well

7.2 Water consumption

In the table 7.1, the amount of water used in each case for the IGCC plant is specified.

The amount of water moved along the steam cycle seems larger in the GE gasifier, but it has to be taken into account that all the water used in the heat recovery for the syngas quenching in the Shell gasifier is also included in the steam cycle, so it will develop more power than the steam cycle in the GE gasifier.

The total amount of water consumed for both cycles is similar, however as it is indicated in the section 7.4, the output power developed in the steam cycle in the Shell gasifier is more than 50% bigger than in the GE gasfier IGCC plant. So considering, that finally the syngas obtained in both cases in equally perfectly quenched and the shift reaction can take place anyway, it could be said that the Shell gasifier has a larger *water efficiency*.

Table 7.1: Water consumption for the IGCC plant in kg/hr/MW

Stream	*GE Gasifier*	*Shell Gasifier*
Steam cycle	70,6	72,4
Steam extra	279,4	273,4
Water quenching	184,7	–
Slurry preparation	42,1	–
Clean-up	22,6	22,1
Heat recovery	–	128,8
Shift reactor	–	106,0
TOTAL	599,4	602,7

7.3 Air Consumption

In the table 7.2 the air used in the IGCC plant is indicated, some differences between each simulation are shown.

Table 7.2: Air consumption for the IGCC plant in kmol/hr/MW

Stream	*GE Gasifier*	*Shell Gasifier*
Coal drying	16,5	34,8
ASU	16,1	10,9
Combustion	23,1	26,5
Nitrogen	27,9	34,4

As it was expected the amount of air used for drying the coal is higher in the Shell gasifier. It is so because the Shell gasifier works with dry feed so the coal is dried until 2% instead the 10% reached in the GE gasifier. However, the air consumption in the ASU is lower than in the Shell gasifier due to more oxygen needs to react in order to warm up the extra content of water that the slurry feed has in the GE gasifier.

As it will be commented in the section 7.4 in the syngas produced in the Shell gasifier the chemical energy is higher, so more oxygen is needed for the complete combustion and as well more extra nitrogen can be included in the process for cooling down the exhaust gases until 1400°C before going through the gas turbine.

7.4 Plant Efficiency

In the figure 7.1, a summary of the efficiency obtained in each simulation can be seen.

The CO_2 capture efficiency is quite low for the Shell gasifier IGCC plant compared to the one obtained in the GE gasifier. This is caused by the combustion of the CH_4 present in the

	Input power	Output power		CO_2 captured	CO_2 capture efficiency	Cold Gas efficiency	Total efficiency
		Gas turbine	Steam cycle				
GE gasifier	**4,53 MW**	**2,47MW**	**0,4 MW**	**1090 kg/hr**	**88,69%**	**73,64%**	**34,08%**
Shell gasifier	**4,53 MW**	**2,65MW**	**0,63 MW**	**919 kg/hr**	**70,00%**	**79,09%**	**38,37%**

Figure 7.1: Results summary for IGCC plants

syngas from the Shell gasifier. This methane has a great heat of combustion but it produces CO_2 which reduces the CO_2 capture efficiency for the plant. This problem could be solved with a auto thermal reforming process for the conversion of methane into other combustible products as shown in the equation 7.1. This process can be carried out with a temperature close to 900°C and a pressure around 35 bar.

$$4CH_4 + O_2 + 2H_2O \rightarrow 4CO + 10H_2 \tag{7.1}$$

A cold gas efficiency analysis is good to be included because it allows a valid comparison between various process at different temperatures. Under same conditions, GE cold gas efficiency should be larger due to the gasification is done at lower temperature. However, the water quenching method used in the GE gasifier makes that some of the fuel has to be burnt in order to vaporize the water, which makes that final cold gas efficiency is reduced. So the Shell cold gas efficiency is larger than in the GE gasifier.

The total efficiency of the system is higher for the Shell gasifier power plant as it was expected, (O.Maurstad u. a.). The IGCC plant with the GE gasifier has an acceptable efficiency, but this is due to the use of a high rank coal in the feed, when working with low rank coal, it would be expected for the GE gasifier efficiency to decrease more sharply than for the Shell gasifier.

7.5 Economics

In order to reach a final decision about which model should be chosen for a particular issue, a detailed economic evaluation should be enclosed for each model. Depending on the pressure and temperature levels that every block is working with, the cost of it can widely vary. It is not the same a pump needing to compress until 40 bar than 140 bar or a gas turbine working at 1400°C or a steam turbine withstanding 520°C, so no rough cost can be approximate.

As well, the raw material used, such as solvent, nitrogen or coal has to be taken into account for the final study. And also the final products like the CO_2 captured or the streams containing sulfur, that has to be led to a Claus process plant, are to be considered.

Chapter 8

Conclusion and Future Considerations

8.1 Conclusion

A coal based IGCC process scheme was simulated in ASPEN plus with a Shell gasifier and in another case with a GE gasifier. The results were discussed and compared. Regarding water consumption, as it is explained in the chapter 7, that the same amount of water is used in both plants but in a different way. Obtaining more power output in the Shell gasifier plant draws the conclusion that the *water efficiency* is larger in the Shell gasifier based IGCC.

Shown also in the chapter 7, that the amount of extra nitrogen that has to be supplied is larger in the Shell gasifier based IGCC plant, but it also allows a larger power output in the gas turbine. A deeper economic analysis should be accomplished in order to prove that it is profitable to purchase this extra amount of nitrogen. However, around 10% extra power output is obtained in the gas turbine which helps to increase the total efficiency of the system.

Comparing the efficiency of both plants, it is quite clear that the Shell gasifier based IGCC plant has a larger electric efficiency for the same coal as feed, so that this technology would be preferable. In case of a lower rank coal, the different between the total efficiency of these two Shell and GE gasifier based IGCC processes would be even larger. So it seems that the Shell gasifier would be suitable at any circumstance, however a final accurate study has to be made about the particular conditions of the plant to be installed.

8.2 Future Considerations

Power produced in the IGCC plants cannot be considered as renewable energy, but the IGCC plants with sour gas removal and CO_2 capture can almost be named as clean energies. This almost zero emissions for the IGCC plants is what makes this technology so attractive to be studied and developed. Year after year and effort after effort the IGCC efficiency are becoming closer to the conventional combined cycle plants. This situation could lead to the optimal solution for the energy production in the future. These are fuel-based power plants, what give the stability that a renewable energy cannot grant and including the main advantage of the zero emissions.

Based on the results obtained in this work, even with the reduction of the electrical efficiency when including a gasifier in the conventional combined cycle plant, a further development of the IGCC plants is recommended.

A suitable type of the gasifier to be used cannot be chosen without a big risk. The economic conditions and the kind of coal available would be a definitive factor for taking the decision. But, based on the results obtained in this document, further development efforts should be dedicated to the Shell gasifier, due to its higher electrical efficiency and cold gas efficiency.

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Appendix A

Simulations

As far as not every single detail can be quoted in this document a copy of the files used for this simulation is attached in the CD-ROM. As well, the complete flowsheet can be seen because it cannot be represented and be understandable in one single sheet of paper.